ON THE PROGENITOR OF THE TYPE II-PLATEAU SUPERNOVA 2003GD IN MESSIER 74[1]

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ABSTRACT

Hubble Space Telescope (*HST*) WFPC2 archival F606W and F300W images obtained within one year prior to the explosion of the nearby Type II supernova (SN) 2003gd in Messier 74 (NGC 628) have been analyzed to isolate the progenitor star. The SN site was located using precise astrometry applied to the *HST* images. Two plausible candidates are identified within $0\rlap{.}''6$ of the SN position in the F606W image. Neither candidate was detected in the F300W image. SN 2003gd appears to be of Type II-plateau (II-P), with age ≈ 87 d on June 17 UT and with low reddening $[E(B-V) = 0.13$ mag]. The most likely of the two progenitor candidates has $M_{V_0} \approx -3.5$ mag (for an extinction-corrected distance modulus of 29.3 mag) and, based on additional color information derived from a high-quality, archival ground-based *I*-band image, we estimate that this star was a red supergiant with initial (zero-age main sequence) mass $M_{\rm ZAMS} \approx 8 - 9\ M_\odot$. This mass estimate is somewhat lower than, but relatively consistent with, recent limits placed on the progenitor masses of other SNe II-P, using *HST* data. Future *HST* imaging with the *HST* Advanced Camera for Surveys, when the SN has faded considerably, will be very useful in pinpointing the exact SN location and securing identification of the progenitor. If our proposed candidate is confirmed, it will be only the sixth SN progenitor ever directly identified.

Subject headings: supernovae: general — supernovae: individual (SN 2003gd, 1999em) — stars: massive — stars: evolution — stars: variables: other — galaxies: individual (Messier 74, NGC 628)

1. INTRODUCTION

Determining which stars give rise to supernovae (SNe) is at the heart of SN research. The main obstacle is that a SN leaves few traces of the progenitor star. Only a small handful of historical SNe (SN 1961V [Zwicky 1964, 1965], SN 1978K [Ryder et al. 1993], SN 1987A [e.g., Gilmozzi et al. 1987; Sonneborn, Altner, & Kirshner 1987], SN 1993J [Aldering, Humphreys, & Richmond 1994; Cohen, Darling, & Porter 1995], and SN 1997bs [Van Dyk et al. 1999, 2000]) have had precursors identified. Additionally, it should be noted that these five SNe were all at least somewhat unusual. Van Dyk, Li, & Filippenko (2003a) recently attempted the direct identification of the progenitors of 16 relatively normal Type II and Type Ib/c SNe, using archival images from the *Hubble Space Telescope* (*HST*). They may have identified the progenitors of the Type II SNe 1999br and 1999ev, the Type Ib SNe 2001B and 2001is, and the Type Ic SN 1999bu. Subsequent follow-up to the tentative identification of the progenitor of the Type II SN 2001du, using an *HST* image of the SN itself, resulted in an upper limit to the progenitor's mass (Van Dyk, Li, & Filippenko 2003b; see also Smartt et al. 2003a).

Here we attempt to identify the progenitor of a recent and relatively nearby Type II-plateau (II-P) event. SN 2003gd was visually discovered by Evans (2003) on June 12.82 UT at about 13.2 mag, and about $20''$ east and $150''$ south of the nucleus of Messier 74 (M74; NGC 628).

McNaught (2003a) confirmed the discovery on CCD images and measured an accurate optical position for the SN of α(J2000) = $1^h 36^m 42\rlap{.}^s 65$, δ(J2000) = $+15°44'19\rlap{.}''9$ (McNaught 2003b). Garnavich & Bass (2003a) obtained near-infrared (0.85–2.4 μm) spectra of SN 2003gd on June 13.46 UT; the strong, broad Paschen-line emission in the *J*-band order of the spectrum led them to classify the SN as Type II. This classification has since been confirmed by Kotak, Meikle, & Smartt (2003) and by Phillips (2003), both groups suggesting that the SN was discovered at an age of $\sim$1–2 months. From ground-based images, Garnavich & Bass (2003b) place a limit on the progenitor star brightness of $R > 24$ mag at four months before discovery.

M74 was also the host to the peculiar Type Ic SN 2002ap (e.g., Mazzali et al. 2002; Leonard et al. 2002c; Foley et al. 2003). Both Sharina, Karachentsev, & Tikhonov (1996) and Sohn & Davidge (1996) measured a distance to M74, based on photometry of the brightest stars in the galaxy. Their consistent results indicate a true (extinction-corrected) distance modulus $\mu_0 = 29.3$ mag, corresponding to a distance of about 7.2 Mpc. Lacking any additional distance information, we assume this distance throughout this paper.

2. ANALYSIS

Pre-SN archival *HST* WFPC2 images containing the SN site were obtained by program GO-9676, using several different pointings, on 2002 August 25 and 28 UT in

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the bands F606W and F300W, for total exposure times of 3100 s and 3000 s, respectively. A summary of the available *HST* data is given in Table 1. Recent multi-band images of SN 2002ap were obtained by GO-9114 in 2003 January using the Advanced Camera for Surveys (ACS), but, unfortunately for us, these were made with the High-Resolution Camera (HRC). The HRC's field-of-view is too small, and the displacement of SN 2002ap from SN 2003gd is too large, for these images to be useful in detecting the progenitor. (Furthermore, at the time of this writing, these images were still proprietary.)

It is absolutely essential to locate the SN site in the *HST* images with high astrometric precision. From a *V*-band image obtained with the Las Campanas Observatory 1.0-m telescope and kindly provided by M. Hamuy, we have measured a precise position for the SN of $\alpha(\text{J2000.0}) = 1^h 36^m 42\overset{s}{.}67$, $\delta(\text{J2000.0}) = +15°44'19\overset{''}{.}7$, with a total uncertainty of $0\overset{''}{.}2$, using the Two Micron All Sky Survey (2MASS) as the astrometric reference. Note the excellent agreement with the position measured by NcNaught (2003b); we adopt the average of these two measurements for the SN position, i.e., $\alpha(\text{J2000.0}) = 1^h 36^m 42\overset{s}{.}66$, $\delta(\text{J2000.0}) = +15°44'19\overset{''}{.}8$. Position data for the SN are summarized in Table 2.

Applying the astrometric method described by Van Dyk et al. (2003a) to a *wmosaic* of the *HST* F606W coadded image pair, U8IXCY02M and U8IXCY03M, utilizing a deep *V*-band image of M74 obtained at the Palomar 1.5-m telescope (see Foley et al. 2003) and again adopting 2MASS as a reference, we are able to isolate the position of the SN on the mosaic to $\pm 0\overset{''}{.}6$. This uncertainty is the SN absolute position uncertainty ($0\overset{''}{.}2$), the uncertainty in the astrometric grid applied to the Palomar image ($0\overset{''}{.}4$), and the uncertainty in the grid further applied to the *HST* mosaic ($0\overset{''}{.}4$), as well as the relative difference between the absolute position measurements ($0\overset{''}{.}1$) and the relative accuracy of the 2MASS astrometry ($\lesssim 0\overset{''}{.}1$), all added in quadrature. The SN site is located on the WF2 chip, and the position uncertainty, at $0\overset{''}{.}1$ pixel^{-1} for the WF chips, therefore corresponds to ± 6 WF pixels.

Since the various pointings are difficult to properly align, both within and between the two bands, we elected to apply the photometry routine HSTphot (Dolphin 2000a, 2000b) to the images in each band in separate units, and to subsequently combine the results. (In fact, we were unable to derive the necessary offsets between the two F300W exposures U8IXCA04M and U8IXCA05M, and the third, U8IXCA03M, as a result of the low signal-to-noise ratio in all of these images.) HSTphot automatically accounts for WFPC2 point-spread function (PSF) variations and charge-transfer effects across the chips, zeropoints, aperture corrections, etc. In this case the HSTphot output was in the flight magnitude system. In Figure 1 we show the SN environment in the F606W band. Two sources, A and B, are detected by HSTphot very near or within the error circle.

Table 3 lists the photometry in the F606W band for Stars A and B. The F606W magnitudes are the uncertainty-weighted average of the photometry

performed on the U8IXCY01M + U8IXCY02M + U8IXCY03M image trio and on the U8IXCA01M + U8IXCA02M image pair. Unfortunately, the F300W exposures were not sensitive enough, since Stars A and B were not detected in the F300W images, to $m_{\text{F300W}} \gtrsim 23.8$ mag (3σ).

Two other stars are seen in Figure 1 about $0\overset{''}{.}5$ to the northeast of the error circle edge; the easternmost one has $m_{\text{F606W}} = 25.09 \pm 0.08$ mag, and the westernmost one has $m_{\text{F606W}} = 25.79 \pm 0.23$ mag (it appears to be somewhat blended). Another two stars are seen near Star A, one $\sim 0\overset{''}{.}4$ due east, and one $\sim 0\overset{''}{.}3$ due south; the eastern one has $m_{\text{F606W}} = 25.97 \pm 0.12$ mag, and the southern one has $m_{\text{F606W}} = 26.02 \pm 0.16$ mag. Several fainter sources are also seen within the error circle in Figure 1, but they are undetected by HSTphot.

3. DISCUSSION

We can attempt to estimate the masses of Stars A and B and therefore comment on the plausibility of each as the likely SN progenitor. For this we need an estimate for the stars' color, as well as the reddening toward the SN, and the metallicity of the SN environment. From the F300W images, limits on the color $m_{\text{F300W}} - m_{\text{F606W}}$ are $\gtrsim -1.6$ mag for Star A and $\gtrsim -2.8$ for Star B. Using the transformations from flight system to Johnson-Cousins magnitudes via SYNPHOT, applied to the Bruzual Spectral Synthetic Atlas (see Van Dyk, Filippenko, & Li 2002), this translates to $U - V \gtrsim -0.9$ mag for Star A. The flight system color for Star B is too blue to realistically transform to a standard color, but it is likely $U - V > -1.5$ mag.

Additional color information for both progenitor candidates can be obtained from a high-quality *I*-band image (seeing $\sim 0\overset{''}{.}9$) obtained with the 2.6-m Nordic Optical Telescope (NOT; see Larsen & Richtler 1999), archived and made available online by NED[2]. Figure 2 shows the SN environment, which is approximately the same field shown in Figure 1. Matching the *I*-band and F606W images was not trivial, even after geometrically transforming one image relative to the other, due to the differences in pixel scale and resolution. However, two faint objects are seen in Figure 2 very near the positions of both Stars A and B (the identification of the counterpart to Star B on the *I*-band image is less certain than that for Star A). Assuming these are the *I*-band counterparts to Stars A and B, this implies that these two stars are red. Using PSF-fitting photometry in DAOPHOT/ALLSTAR (Stetson 1987, 1992) within IRAF[3] and, calibrating this image using the comparison stars in Foley et al. (2003), we find the *I*-band magnitudes for the two stars listed in Table 3. Applying the transformations derived from SYNPHOT we convert $m_{\text{F606W}} - I$ for both stars to $V - I$, and m_{F606W} to V (for such red stars, V is ~ 0.8 mag fainter than m_{F606W}); these values, and their estimated uncertainties, are also listed in Table 3.

We have obtained *BVRI* images of SN 2003gd on a number of epochs with the Katzman Automatic Imaging Telescope (KAIT; see Li et al. 2000; Filippenko et

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al. 2001). Again, we have calibrated these images using the comparison stars for SN 2002ap in Foley et al. (2003). The SN photometry is listed in Table 4. The SN was already quite red at the time of discovery. Unfortunately, the SN color is subject to a degeneracy between the SN age and the reddening. We can try to break this degeneracy through a comparison with the very well-studied Type II-P SN 1999em in NGC 1637 (Hamuy et al. 2001; see also Leonard et al. 2002a and Elmhamdi et al. 2003).

In Figure 3 we show the $BVRI$ light curves of SN 2003gd and for comparison the light curves of SN 1999em, adjusted to the true distance modulus of M74. No reddening correction is made to the light curve of SN 1999em to match that of SN 2003gd. (However, we have adjusted the light curves of both SNe in time to find the best match.) Similarly, in Figure 4 we show the color evolution of SN 2003gd, and for comparison, that of SN 1999em, with both SNe corrected for reddening [$E(B-V) = 0.1$ mag for SN 1999em, Leonard et al. 2002c; $E(B-V) = 0.13$ mag for SN 2003gd, see below]. Both figures imply rather convincingly that SN 2003gd is also a SN II-P and that it was quite old at the time of discovery (near the end of the plateau phase of the light curves). Similar to SN 1999em, SN 2003gd suffers relatively low reddening, which is also supported by the lack of interstellar Na I D absorption, as well as low continuum polarization seen in spectra of SN 2003gd we have obtained at the Lick 3-m and Keck 10-m telescopes. Although the photometry for the two SNe II-P agrees quite well during the plateau phase, it is most striking how much fainter SN 2003gd is relative to SN 1999em in the late-time nebular phase. The faint nebular-phase tail and large post-plateau drop may be suggestive of low ejected ^{56}Ni mass, similar to the subluminous SNe II-P SN 1997D and 1999br (Benetti et al. 2001; Zampieri et al. 2003). A more detailed study of SN 2003gd is clearly warranted.

From the plateau we estimate an age for SN 2003gd of 87 ± 3 d on June 17 UT, placing the date of explosion at about March 17 UT, consistent with the range of explosion dates between February and April suggested by Garnavich & Bass (2003b). Additionally, we estimate the total reddening to SN 2003gd as $E(B-V) = 0.13 \pm 0.03$ mag [the Galactic reddening toward M74 is itself quite low, $E(B-V) = 0.07$ mag; Schlegel, Finkbeiner, & Davis 1998; and NED].

In Figure 5 we show the absolute V magnitude and $U - V$ color limits from the HST photometry for the two progenitor candidates, corrected for reddening to the SN, assuming the Cardelli, Clayton, & Mathis (1989) reddening law, and adjusted for the true M74 distance modulus. SN 2003gd occurred about $161''$ southeast of the M74 nucleus, or at $R/R_{25} \approx 0.5$. At this nuclear distance, van Zee et al. (1998) represent the relative oxygen abundance as $\log(O/H) + 12 \approx 9$ dex. The metallicity in the SN 2003gd environment, then, is possibly ~1.5 times greater than solar (where the solar O/H abundance is 8.8 dex; Grevesse & Sauval 1998). In Figure 5 we therefore show for comparison the model stellar evolutionary tracks for a range of masses from Lejeune & Schaerer (2001), assuming enhanced mass loss for the most massive stars and a metallicity $Z = 0.04$ for the SN environment.

From the positions of Stars A and B in Figure 5, we can-

not rule out that the SN progenitor was a blue star. However, except for the most massive stars, which may evolve back to the blue toward the end of their lives (such as seen for the 40 $M_\odot$ model), we do not expect SN II progenitors to generally occupy this color region [$(U - V)_0 \approx -1$ to -2 mag], since lower-mass stars are still on (or are just barely off) the main sequence and therefore not sufficiently evolved. Also, we expect SN II-P progenitors to be red supergiants, since both the optical P-Cygni spectral line profiles and the plateau phase of the SN light curve (arising from a hydrogen recombination wave in the envelope) require such extensive hydrogen envelopes. Furthermore, the lack of radio emission from SN 2003gd (C. J. Stockdale et al. 2003, private communication) implies a paucity of circumstellar matter, providing additional evidence that most of the progenitor's matter was still contained in the star itself at the time of explosion.

In Figure 6 we show the absolute magnitude and color for Stars A and B from the combined HST and NOT photometry, again corrected for reddening to the SN and adjusted for the true M74 distance modulus. For comparison we again show the Lejeune & Schaerer (2001) evolutionary tracks, as in Figure 5 (for 9 $M_\odot$ we also show the track corresponding to solar metallicity, $Z = 0.02$; as can be seen, little difference exists in the red between the tracks of different metallicity). From Figure 6 it appears that both stars are red supergiants, and that Star A had an initial (zero-age main sequence) mass $M_{\rm ZAMS} \approx 8$–9 $M_\odot$. The fainter Star B appears to have had an initial mass $M_{\rm ZAMS} \approx 5$ $M_\odot$, which is formally below the theoretical lower limit for core-collapse SNe (~ 8 $M_\odot$; e.g., Woosley & Weaver 1986).

One of the two stars is most likely the progenitor: the F606W detection limit, $m_{\rm F606W} = 27.3$ mag (3σ), when corrected for the true M74 distance modulus and assuming stars of the same reddening-corrected $V - I$ as Stars A and B, corresponds to $M_{V_0} \approx -1.6$ mag and therefore to initial masses well below the core-collapse limit. Thus, we can probably rule out that the progenitor is not detected in the F606W image. Although Star A is farther from the SN position than Star B, and just outside the edge of the error circle, we consider Star A to be the most likely progenitor candidate, based on its estimated initial mass. From Figure 2 it also appears to be the most plausible candidate, being the brightest object in the I band within the SN's larger, $\sim 1''$ radius, environment. (Although of comparable brightness to Stars A and B in F606W, the four other stars mentioned in § 2 which are outside, but near, the error circle do not have clearly identifiable counterparts on the I-band image, implying that these stars are bluer than Stars A and B and can probably be discounted as progenitor candidates.) The estimate for the SN 2003dg progenitor mass is lower than the limits derived for the nearby SNe II-P 1999gi (15^{+5}_{-3} $M_\odot$; Leonard et al. 2002b) and 1999em (20 ± 5 $M_\odot$; Leonard et al. 2003), but is consistent with that for the SN II-P 2001du (13^{+7}_{-4} $M_\odot$; Van Dyk et al. 2003b). Our estimates for the absolute brightness and initial mass for the SN 2003gd progenitor are consistent with those reported by Smartt, Maund, & Hendry (2003b).

4. CONCLUSIONS

Examining *HST* archival WFPC2 images of the Type II-P SN 2003gd in M74 obtained before explosion, we have isolated two possible SN progenitor stars. Although we cannot exclude a blue SN progenitor, it is more likely that the progenitor was red. This is further supported by the brightness of the two stars on a ground-based archival *I*-band image. SN 2003gd is an old SN II-P, and we have estimated that its reddening is quite low, $E(B-V) = 0.13$ mag, similar to that of the well-studied SN II-P 1999em. We estimate that the more likely candidate of the two stars had an initial mass $M_{\rm ZAMS} \approx 8$–9 $M_\odot$ which, together with mass limits derived for other SNe II-P, suggests that such SNe II-P arise from massive stars at the lower extreme of the possible mass range for core collapse.

It would be most fruitful to recover the SN in multiple bands with *HST* at high spatial resolution, preferably with ACS, when the SN has significantly dimmed. This will allow us to pinpoint the SN's exact location on the preexplosion images and thus be definitive about the progenitor's identification. If our proposed candidate is confirmed, it will be only the sixth SN progenitor ever directly identified. Additionally, the multiband imaging of the stars in the environment of the fading SN would provide possible further constraints on the age and mass of the progenitor star, based on the characteristics of its surviving neighbors.

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Table 1
Summary of *HST* Observations[a]

Date (UT)	Filter	Exp. Time (s)	*HST* Dataset
2002 Aug 25	F606W	500	U8IXCA01M
			U8IXCA02M
	F300W	1000	U8IXCA03M
			U8IXCA04M
			U8IXCA05M
2002 Aug 28	F606W	700	U8IXCY01M
			U8IXCY02M
			U8IXCY03M

[a]Program GO-9676.

Table 2
Position Data for SN 2003gd

α(J2000)	δ(J2000)	Uncertainty	Source
$1^h36^m42^s\!.65$	$+15°44'19''\!.9$	$0''\!.1$[a]	McNaught (2003b)
$1^h36^m42^s\!.67$	$+15°44'19''\!.7$	$0''\!.2$[b]	This paper
$1^h36^m42^s\!.66$	$+15°44'19''\!.8$	$0''\!.2$[b]	Average

[a]Uncertainty in each coordinate.

[b]Total uncertainty.

Table 3
Photometry of Stars Near SN 2003gd (mag)

Star	m_{F606W}	I	$V-I$	V
A	25.39 ± 0.09	22.5 ± 0.2	3.6 ± 0.3	26.2 ± 0.2
B	26.56 ± 0.24	23.8 ± 0.4	3.5 ± 0.4	27.4 ± 0.3

Table 4
KAIT Photometry of SN 2003gd (mag)

UT date	JD–2450000	B	V	R	I
Jun 17	2807.99	15.44(04)	14.14(04)	13.65(03)	13.26(03)
Jun 20	2810.98	15.54(02)	14.19(02)	13.71(02)	13.32(02)
Jun 22	2812.97	15.55(02)	14.24(02)	13.72(03)	13.34(02)
Jun 27	2817.96	15.70(02)	14.33(02)	13.81(03)	13.43(02)
Jun 29	2819.97	15.74(02)	14.37(03)	13.82(02)	13.42(03)
Jul 3	2823.95	15.88(02)	14.46(02)	13.89(02)	13.50(02)
Jul 5	2825.97	15.94(02)	14.49(02)	13.93(02)	13.52(02)
Jul 7	2827.95	16.03(02)	14.56(02)	13.97(02)	13.56(02)
Jul 9	2829.96	16.15(02)	14.65(02)	14.05(02)	13.64(02)
Jul 11	2831.95	16.25(02)	14.74(03)	14.15(02)	13.75(03)
Jul 13	2833.95	16.35(05)	14.87(03)	14.24(03)	13.81(02)
Jul 15	2835.95	16.62(04)	15.07(03)	14.42(03)	13.98(03)
Jul 17	2837.97	16.91(02)	15.33(02)	14.62(02)	14.17(03)
Jul 23	2843.96	18.31(02)	16.85(02)	15.94(03)	15.41(04)
Jul 26	2846.97	18.69(03)	17.32(03)	16.26(03)	15.69(03)
Jul 29	2849.97	18.94(05)	17.42(02)	16.40(02)	15.81(03)
Aug 4	2855.97	19.05(05)	17.45(03)	16.34(03)	15.81(04)
Aug 10	2861.97	19.07(06)	17.56(03)	16.47(02)	15.89(03)
Aug 19	2870.97	19.14(07)	17.66(03)	16.56(02)	16.00(03)

Note: uncertainties (hundredths of a magnitude) are indicated in parentheses.

Fig. 1.— The site of SN 2003gd in the archival 3100-s F606W composite image from 2002 late-August. The error circle has radius $0\rlap{.}''6$. Two progenitor candidates, Stars A and B, near or within the circle are indicated with short line segments.

Fig. 2.— The environment of SN 2003gd, as seen in an I-band image of the host galaxy, M74, obtained with the 2.6-m Nordic Optical Telescope (see Larsen & Richtler 1999). Two objects are seen in the image at the approximate locations of Stars A and B, and are labelled accordingly in the figure.
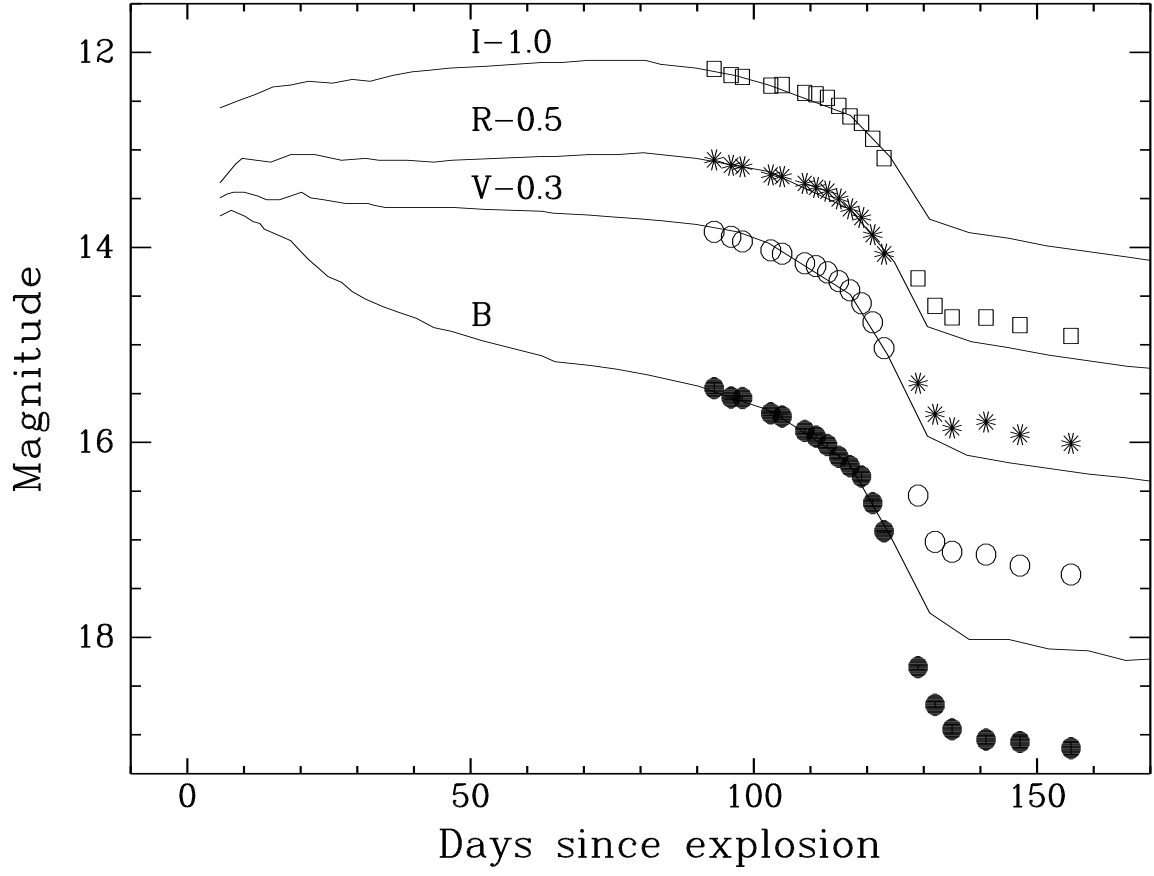
Fig. 3.— The *BVRI* light curves for SN 2003gd from KAIT observations. For comparison, the light curves for the well-studied Type II-plateau SN 1999em (Hamuy et al. 2001) are shown, adjusted to the true distance modulus of M74. No additional reddening correction has been applied to the SN 1999em light curves.
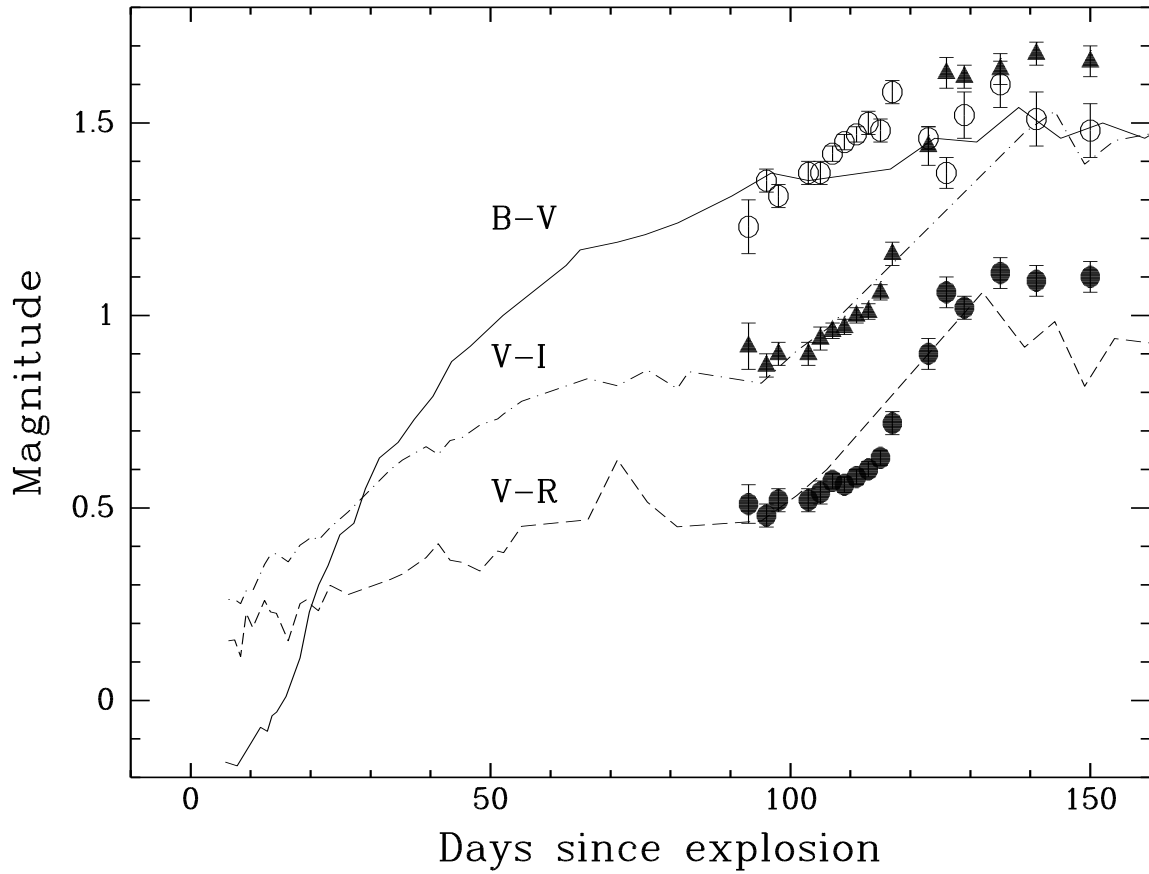
Fig. 4.— The $B - V$ (*open circles*), $V - R$ (*filled circles*), and $V - I$ (*stars*) colors of SN 2003gd from KAIT observations, corrected for an assumed reddening $E(B - V) = 0.13$ mag. For comparison, the reddening-corrected color evolution for SN 1999em [Hamuy et al. 2001; $E(B - V) = 0.1$ mag] is shown for $B - V$ (*solid line*), $V - R$ (*dashed line*), and $V - I$ (*dot-dashed line*).
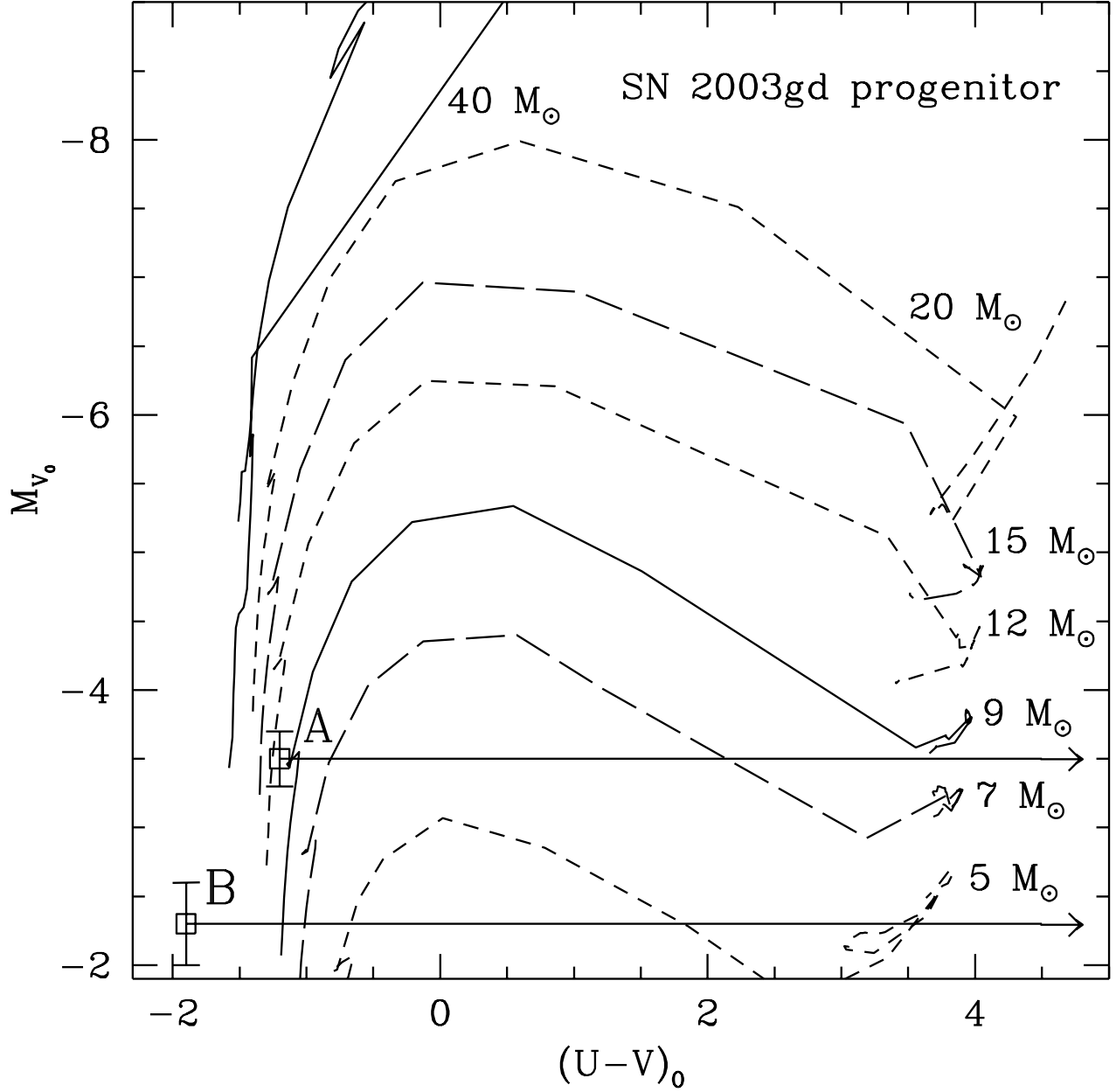
Fig. 5.— Intrinsic color-magnitude diagram showing model stellar evolutionary tracks (alternating *long-dashed lines*, *short-dashed lines*, and *solid lines*) for a range of masses from Lejeune & Schaerer (2001), with enhanced mass loss for the most massive stars and a metallicity $Z = 0.04$. Also shown are the absolute extinction-free magnitudes and reddening-corrected color limits for the two progenitor candidates, Stars A and B, assuming $E(B - V) = 0.13$ mag and an extinction-corrected distance modulus to M74 of $\mu_0 = 29.3$ mag.
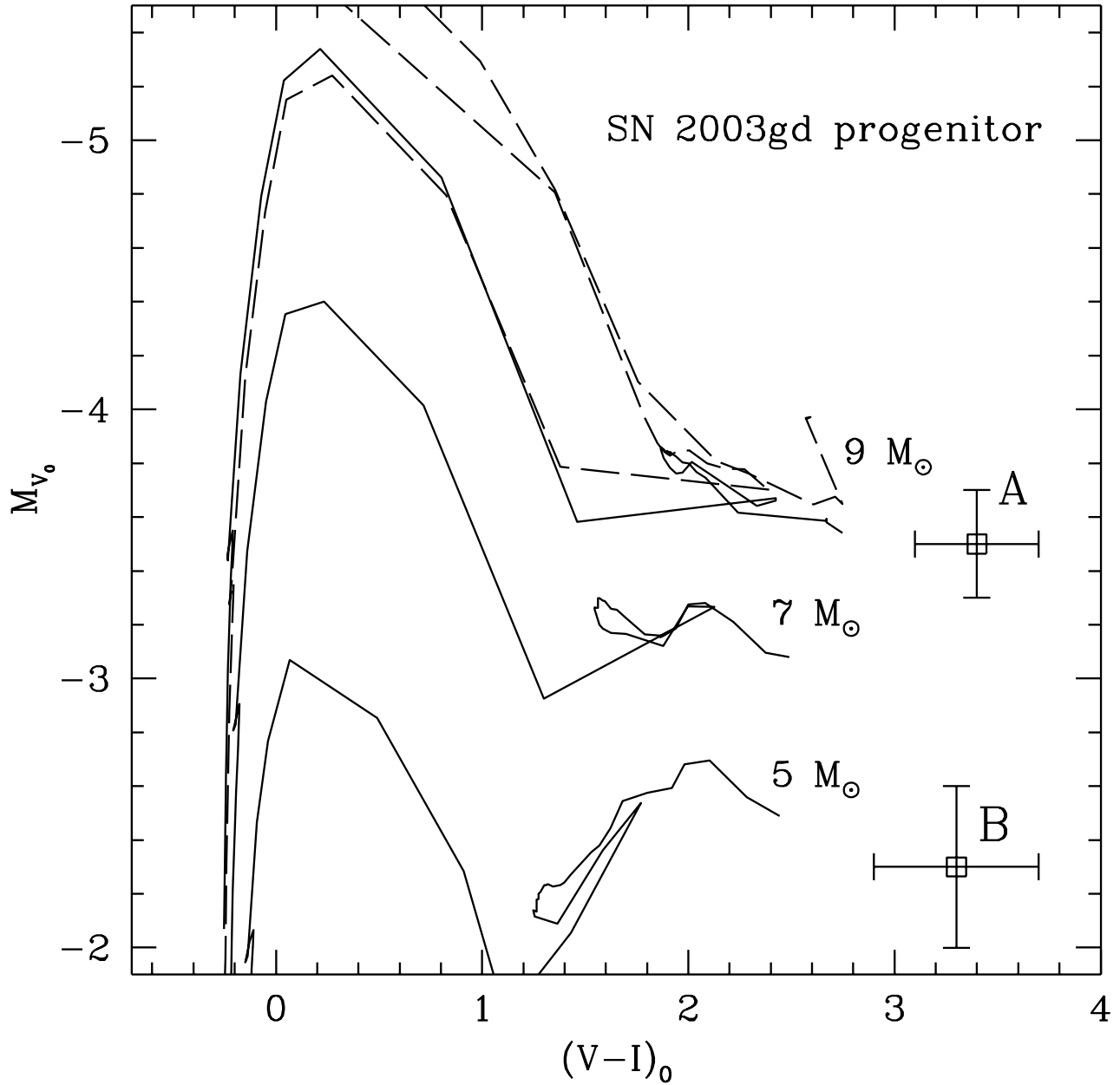
Fig. 6.— Intrinsic color-magnitude diagram showing model stellar evolutionary tracks for a range of masses from Lejeune & Schaerer (2001), with enhanced mass loss for the most massive stars and a metallicity $Z = 0.04$ (*solid lines*), and the track for 9 $M_\odot$ and metallicity $Z = 0.02$ (*dashed line*). Also shown are the absolute extinction-free magnitudes and reddening-corrected colors for the two progenitor candidates, Stars A and B, assuming $E(B - V) = 0.13$ mag and an extinction-corrected distance modulus to M74 of $\mu_0 = 29.3$ mag.

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